Torsional Appearance of the Anterior Cruciate Ligament Explaining "Ribbon" and Double-Bundle Concepts: A Cadaver-based Study

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Purpose: To investigate the effect of the anterior cruciate ligament (ACL) torsion in 90° knee flexion on the morphological appearance of the ACL. **Methods:** Sixty knees from fresh frozen anatomical specimens were dissected. Eighteen knees were excluded according to selection criteria (torn ACL, mucoid degeneration of the ACL, arthritic lesions of the notch, or knees harboring synovial inflammatory pathologies). After the removal of the synovial membrane, the morphology of the ligamentous fibers of the ACL and the twist were analyzed. Twisting of the ACL was measured using a goniometer in 90° knee flexion and defined by the angle of external rotation of the femur on the axis of the tibia required to visualize a flat ACL. The orientation of tibial and femoral footprint was described in a coronal plane for the tibia and a sagittal plane for the femur. **Results:** In the 42 knees that were finally included, the ACL was always displayed as a single ribbon-like structure. The torsion of the fibers was on average 83.6° (± 9.4°) in 90° knee flexion. The twisting could be explained by the different orientations of the femoral (vertical in a sagittal plane) and tibial (horizontal in a coronal plane) footprints. An intraligamentous proximal cleavage area was encountered in 11 cases (i.e., 26%). **Conclusions:** The ACL is a twisted structure with 83.6° of external torsion of fibers in 90° knee flexion. It is the torsion in the fibers, due to the relative position of bone insertions, which gives the ACL the appearance of being double bundle. **Clinical Relevance:** The concept of the torsional flat structure of the native ACL may be of importance during ACL reconstruction, both in terms of graft choice (flat rather than cylindrical) and of technical positioning (torsion).

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Surgical reconstruction of the anterior cruciate ligament (ACL) is a common procedure[1] with good functional outcomes,[2,3] but only 25% of patients are classified as IKDC A (International Knee Documentation Committee). The current objective is to make an anatomical reconstruction.[4,5] The anatomy of the ACL has proven to be a controversial subject.[5] Since the work of the Weber brothers, the ACL has been considered to be composed of 2 bundles: the anteromedial (AM) and the posterolateral (PL).[6-10] Smigielski et al.[11] described the ACL as a single flat bundle extended like a ribbon after the dissection of 111 knees from cadavers. His detailed anatomical study described the ribbon-like structure of the ACL: "A total of 2-3 mm from its bony femoral insertion, the ACL formed a flat ribbon without a clear separation between AM and PL bundles."

This discrepancy in the morphologies (i.e., a double bundle vs a ribbon) could be explained by twisting of the fibers of an ACL as a ribbon around its main axis, thereby giving rise to the typical double-bundle appearance in 90° knee flexion. The purpose of this study was to investigate the effect of the ACL torsion in 90° knee flexion on the morphological appearance of the ACL. We hypothesized that the ACL would have a ribbon-like shape, undergoing a twist along its main axis that is imposed by the orientation of its femoral and tibial footprints in 90° knee flexion.

Methods

Sixty knees from fresh frozen cadavers stored at +4°C (30 right knees and 30 left knees, 18 women and 12 men,

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median age of 76 years [57-92 years]) were dissected by the first author (T.N.). The average time since death was 1.1 months (1-2 months). This work was performed according to a standardized protocol in keeping with the ethics standards in France for cadaveric studies. The only criterion for inclusion was that the cadaver knees should not have been subjected to prior surgical procedures. Knees found to have a torn ACL, mucoid degeneration of the ACL, arthritic lesions of the notch, or knees harboring synovial inflammatory pathologies over the course of the dissections were excluded.

After being thawed on the day before the study, the knee was approached anteromedially. The patella was laterally dislocated, and the Hoffa fat pad was removed while preserving the lateral meniscus. After ensuring its integrity in 90° knee flexion, the anterior synovial membrane of the ACL was dissected from the femoral insertion to the tibial footprints. The distinction between the ligamentous fibers and the synovial membrane was carried out by using a microsurgical magnifying glass with lens magnification × 3.6 (Keeler, Windsor, Berkshire, England) (e.g., pearly color of the fibers that are organized into bundles, limited thickness and viscous appearance, as well as transparency of the synovial membrane). The removed synovial membrane was analyzed with the microsurgical magnifying glass, showing that neither ligamentous fiber was present.

The lateral condyle, the ACL, and the tibial plateau were then removed as a single piece by sagittal cutting of the medial condyle and axial to the tibial metaphysis (5 mm in thickness) with an oscillating saw in 90° knee flexion and by the first author (T.N.) (Fig 1). We have ensured that the tibial bone section is perpendicular to the mechanical axis of the tibia in 90° knee flexion (avoid varus/valgus). Any tibial slope in the section was obtained freehand but with control of the thicknesses at the end of the osseous section to verify the anterior and posterior thicknesses. The distal femoral section was obtained parallel to the line joining the posterior tibial plateaus in 90° knee flexion to define the neutral position of rotation. Landmarks for the calculation of the torsion in an axial view were the axis of the lateral femoral condyle in the neutral position of rotation and when the ACL was flat.

Mobilizing the lateral condyle, the dissection was carried out posteriorly at the femoral and tibial insertions while retaining all of the ligamentous fibers. Four successive measures were then carried out in 90° knee flexion. This position at 90° was verified by external assessment using landmarks (the anatomical axis of the femur in a sagittal view and the table seating plan without a tibial slope).

- The morphology of the ACL was analyzed quantitatively, with or without a cleavage area, in the axis of the ACL. The caliber of the ACL without the synovial membrane was measured at 1.5 cm from its tibial insertion (anteroposteriorly/thickness and mediolaterally/width) with a manual caliper.
- An external rotation of the femur on the fixed tibia around a vertical axis (corresponding to an internal rotation of the tibia) was performed. When the ACL appeared to be flat (parallel alignment of the orientation of the collagen fibers), the angle of rotation was measured, thus defining the torsion of the ACL. The measurement was performed by the first author (T.N.) by using a Comed goniometer (Strasbourg, France) with an accuracy of ±1°. The angle was measured with a craniocaudal aspect starting from a neutral position that was marked on the working surface (Fig 2).
- The ACL was then sectioned from its femoral and tibial footprints. The appearance and orientation of the main axis of the femoral and tibial footprints were evaluated relative to the posterior diaphyseal cortical bone in a sagittal plane and at the edge behind the tibia in a coronal plane.
- Measurements of the anterior and posterior sides of the ACL as a flat bundle were taken on the table after cutting. All of the length measurements were taken with the manual caliper. The reproducibility of measures was ensured by the realization of dissection and cuttings by the first author (T.N.) and the use of a known mark quoted in a systematic way.

The data were collected into an Excel program (Microsoft, Redmond, WA). The statistical calculations (mean, standard deviation, variance) were carried out using the Excel program.

Results

Eighteen knees were excluded according to the exclusion criteria: torn ACL (8), mucoid degeneration of the ACL (2), arthritic lesions of the notch (7), or knees harboring synovial inflammatory pathologies (1). Forty-two cadaver knees (15 women and 6 men, median age of 80.6 years [62-92 years]) were finally included (21 right knees, 21 left knees).

- In all cases, without the synovial membrane, the ACL presented as a single structure macroscopically (Fig 3). The mediolateral caliber (width) and the anteroposterior caliber (thickness) at 1.5 cm from the tibial footprint of the ACL were 5.9 mm (±1.32 mm) and 2.7 mm (±0.47 mm), respectively. An intraligamentous proximal cleavage area was encountered in 11 cases (i.e., 26%). It was always incomplete (proximal third) and nontransfixing (continuity of ligament's fibers) (Fig 4).
- The ACL was observed to be flat macroscopically (parallel alignment of the orientation of the collagen fibers) after femoral external rotation along the vertical axis of the tibia. The rotation required to obtain a flat structure was, on average, 83.6° ± 9.4° (Fig 5).

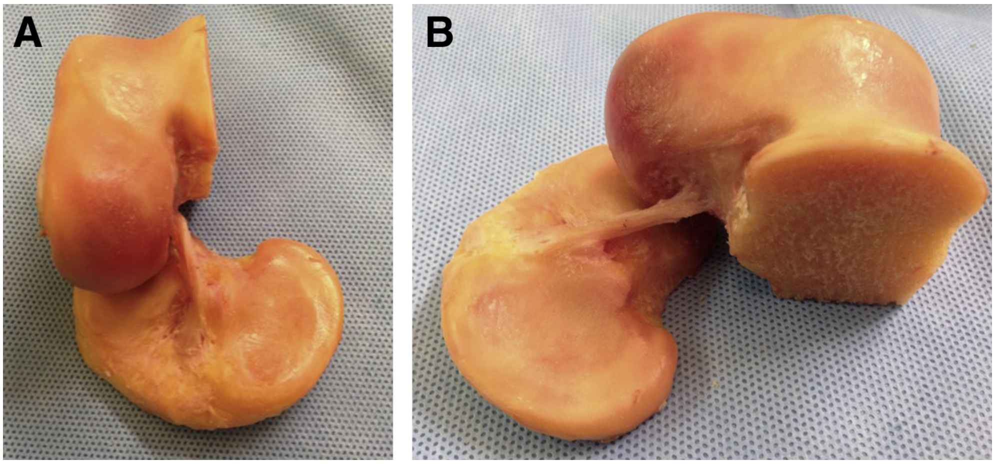

Fig 1. Bone cuts (frontal view A, sagittal view B) allowing the lateral condyle and the tibial plateau to be discerned and allowing the posterior dissection of the synovial membrane. Bone cuts were made after landmarks (flexion, rotation) to permit measurements.

- The femoral and tibial footprints were always thin. Femoral insertion, in the sagittal plane, had the shape of a comma and followed the cartilage of the femoral condyle. At the tibia, the footprint was convex facing forward in the coronal plane, as a "C" in 38% or as an "inverted U" in 62% of cases. Its main axis was part of the frontal plane.
- After cutting the ACL from its footprints, the main length of the anterior edge was 34.8 mm on average (28.6-43.1 mm) and the posterior edge was 23.7 mm (20.2-27.6 mm) (Fig 6).

Discussion

This study shows that the ACL has a ribbon-like shape that twists, giving the impression of separate bundles. The femoral and tibial footprints were linear and divergent: the main axis of the femoral footprint was in a sagittal plane, whereas that of the tibial footprint was in a coronal plane.

The description of the femoral and tibial footprints of the ACL is still a matter of debate in the literature (e.g., linear or oval).[6,9,10,12-14] Although Odensten et al. described the anatomy in terms of 2 or 3 bundles,[15-17] it is generally acknowledged that the collagen fibers are organized into 2 AM and PL bundles with various morphologic and functional properties.[7,18-24] For Skelley et al.,[25] most microstructures of the ACL appear to follow a linear gradient across the ACL, rather than varying by the bundle. Smigielski et al.[11,26] described a revisited anatomy of the ACL after the microsurgical dissection of cadaver knees, referred to as "The Ribbon concept." Our study confirms this theory and describes the link between the 2 concepts (i.e., a ribbon and a double bundle). Previous anatomical studies have described this torsion,[27] and biomechanical studies have suggested that there is an enhanced resistance to tearing with the torsion of an allograft of the ACL close to 90° knee flexion.[28] Van Kampen et al.[29,30] found that there was a decrease in the anterior slackness after the torsion of the transplant on anatomical subjects, regardless of the degree of torsion.

Support for the concept of a ribbon twisted on itself is provided by 2 anatomical arguments as follows.

The first argument is that when the knee is flexed at 90°, the orientation of the main axis of the femoral and tibial of footprints, the ACL is divergent and approximates a right angle: in a sagittal plane at the femur and in a coronal plane at the tibia. The femoral footprint extends to the posterior cortical part of the femur and is a backward-facing convex entity,[11] whereas the tibial "C"-shaped footprint is a forward-facing convex entity.[31,32] A flat bundle between 2 footprints with

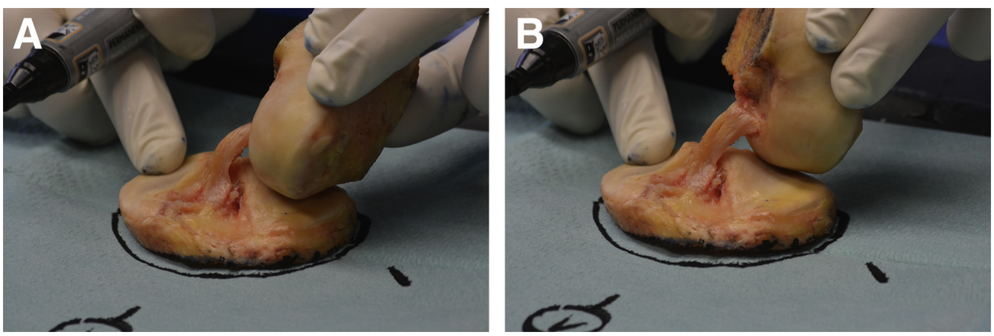

Fig 2. Position in neutral rotation and with flexion 90° (A) and position after the rotation of the lateral condyle to obtain a flat structure (B) were marked on the working surface. These landmarks allow measurements of torsion.

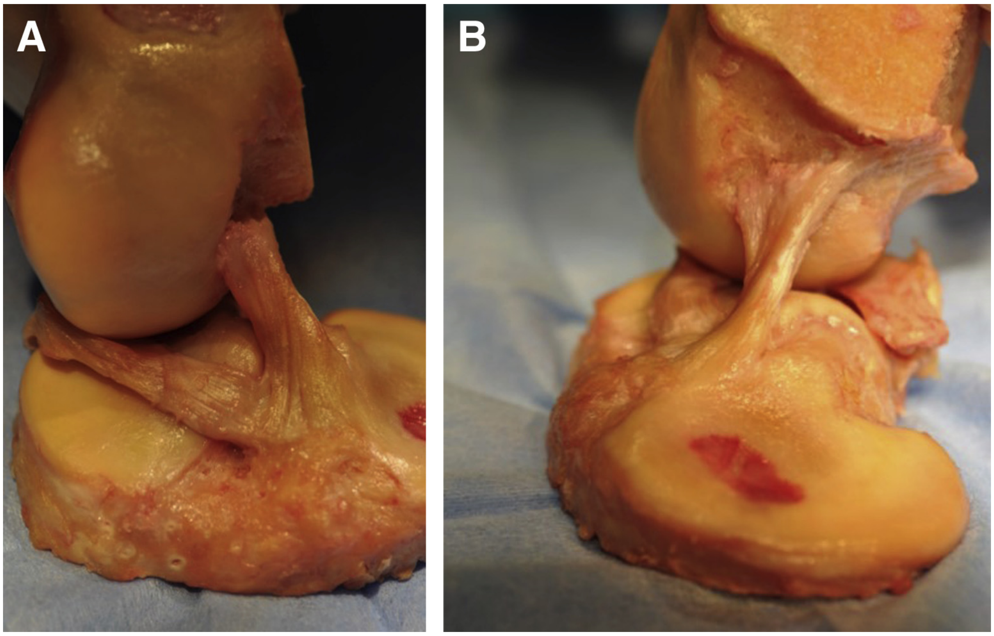

Fig 3. Single-bundle ribbon-like aspect of the anterior cruciate ligament without the synovial membrane from a (A) frontal and (B) sagittal views. Bone cuts allow us to analyze the torsion of the anterior cruciate ligament by the mobilization of the lateral condyle.

different orientations may give the shape of a double bundle or at least a twisted ligament while it is a ribbon. In light of this torsion, the presentation in 90° knee flexion gives rise to the false appearance of a double bundle.[7,18,33] According to Mochizuki et al.,[27] this appearance increases on flexing movement. Furthermore, in 26% of cases, we found an upper intraligamentous cleavage area, always less than one-third of the total length of the ACL. The cleavage area was incomplete and nontransfixing in all of the cases, although it could give rise to a dissection artifact if it is extended distally. Amis and Dawkins[18] investigated the fiber bundle anatomy of the ACL and provided evidence of several bundles, underscoring the fact that this was linked to advanced age. Ultimately, freed of its bony insertions, the ACL has a trapezoid shape with a posterior edge that is shorter than the anterior edge which corresponds to the typical AM bundle that is longer than the PL bundle.[6,34,35] The highlighting of this cleavage is a discovery of the study, explaining

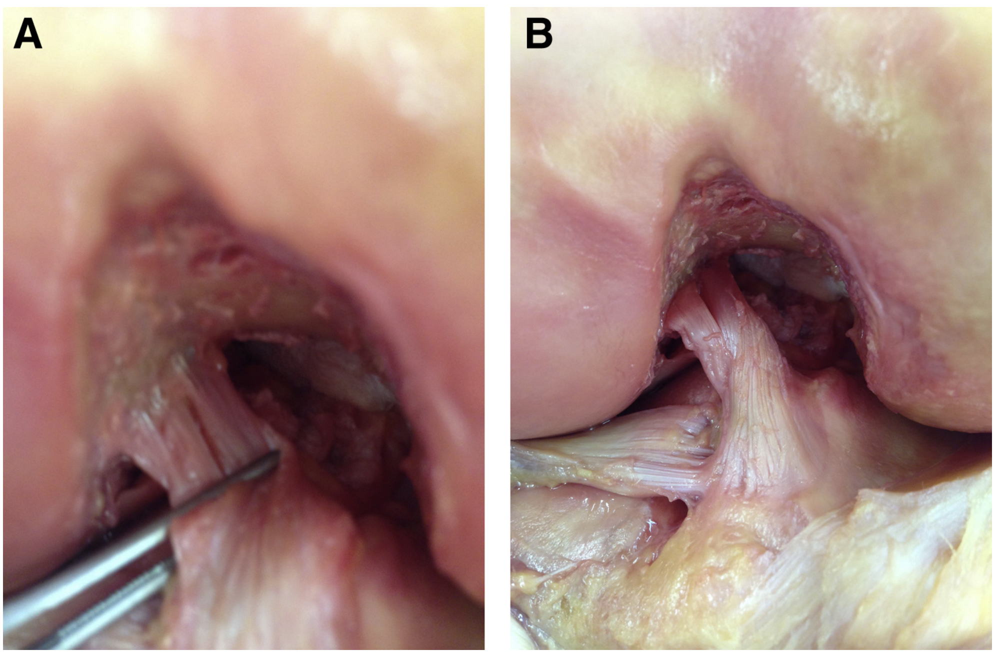

Fig 4. In our study, we have found in 26% an upper cleavage area (A), close to the femoral footprint (B). This area was incomplete and nontransfixing in all of the cases.

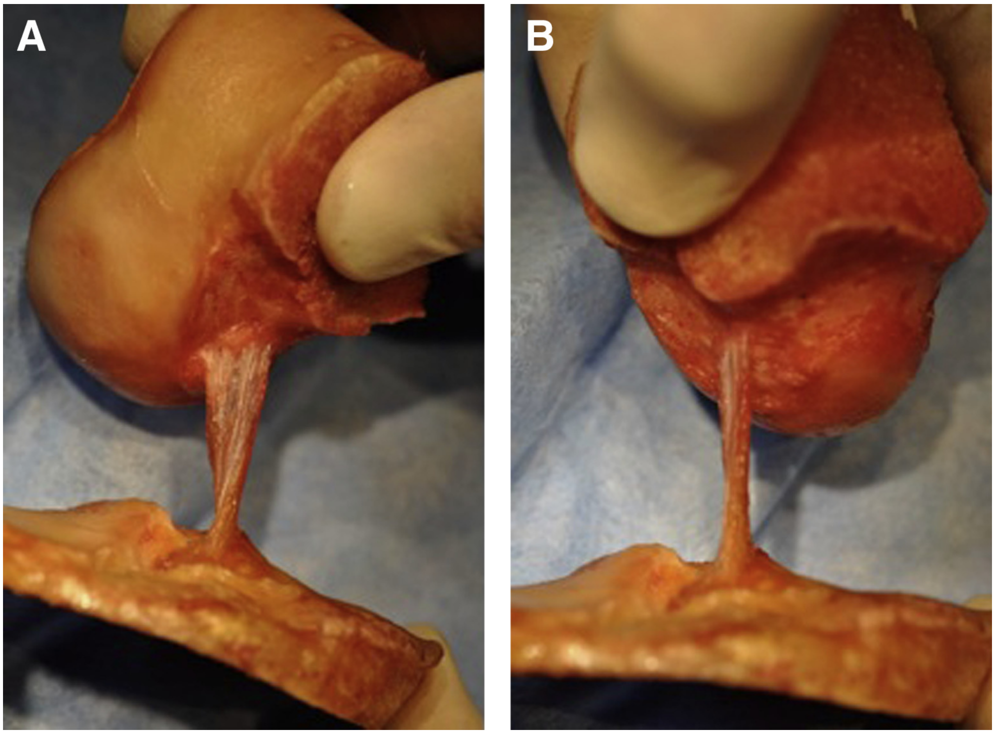

Fig 5. Following the internal rotation of the tibia under the femur, the fibers of the anterior cruciate ligament run parallel to each other and form a single flat bundle (A to B). In this example, the 90° flexion was not clearly defined.

certain artifices of dissection. In fact, if this cleavage was artificially extended, we obtained an ACL in 2 bundles. Our team cannot explain the fact that Smigielski did not find it. Smigielski described a flat ACL without twisting: "This is a detailed anatomical study describing the ribbon-like structure of the ACL from its femoral insertion to midsubstance. The ACL formed a flat ribbon without a clear separation between AM and PL bundles."[11]

The second argument is embryologic. Ferretti et al.[36] provided evidence for a parallel orientation of the ACL fibers in fetus and made the hypothesis that ACL follows the torsion of the lower limbs during embryonic development. In this study of Ferretti, the anatomy described was one "gross anatomy" with a histological evaluation in sagittal and transverse views. In our study, the ACL was not transversely sectioned. The gross observations of Ferretti revealed the presence of 2 bundles: AM and PL. We can hypothesize that our proximal cleavage is the result of nonfusion of the fetal double bundle during development.

Limitations

This study has its limitations. All measures were made for 90° knee flexion, but degrees of flexion can change the values of measures. Furthermore, we do not have a validated technique to ensure the degrees of flexion for all specimens. The cutting by 1 author does not make this reliable or reproducible. Preservation of anatomical specimens by freezing assists in the dissection of the synovial membrane compared with those that have been embalmed.[18] In this study, cadavers were mostly elderly and female, and significant gender-specific differences in measurements have been reported.[37] There is a risk of overinterpretation in light of the limited number of measurements for this study. Furthermore, the measurement of torsion was performed after cutting the bone to identify the lateral condyle, which could have given rise to approximate measurements. Finally, although the use of a microsurgical magnifying glass facilitated the distinction of the synovial membrane from ligamentous tissue, only a histological study

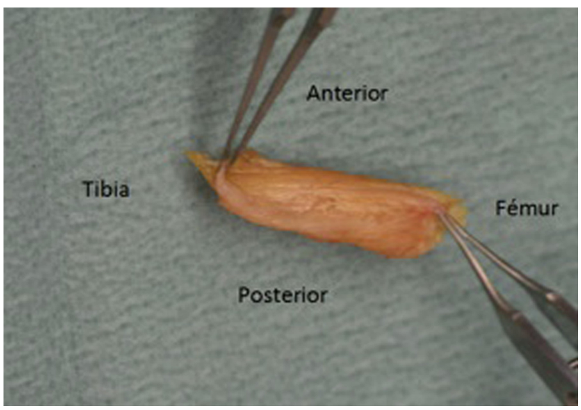

Fig 6. Rectangular shape of the anterior cruciate ligament after the section of insertions. We have made measurements of the lengths of the anterior and posterior sides of the anterior cruciate ligament as flat bundles on the table.

of the dissection remnants could confirm that we did not remove any ligamentous fibers.

Conclusions

The ACL is a twisted structure with 83.6° of external torsion of fibers in 90° knee flexion. It is the torsion in the fibers, due to the relative position of bone insertions, which gives the ACL the appearance of being double bundle.

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